PHOTOMETRIC PROPERTIES OF LONG-PERIOD VARIABLES IN THE LARGE MAGELLANIC CLOUD

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Abstract Approximately four thousand light curves of red variable stars in the Large Magellanic Cloud (LMC) were selected from the 2.3-year duration MOA database by a period analysis using the Phase Dispersion Minimization method. Their optical features (amplitudes, periodicities, position in CMD) were investigated. Stars with large amplitudes and high periodicities were distributed on the only one strip amongst multiple structure on the LMC period-luminosity relation. In the CMD, the five strips were located in the order of the period. The stars with characterized light curves were also discussed.

Keywords: Red variables, period-luminosity relation, massive photometry

1. Introduction

The multiple and complicated period-luminosity relation for red variables in the LMC had been discovered using the microlensing database (Wood, Alcock, Allsman et al. 1999, Wood 2000). Although the Mira sequence (Feast, Glass, Whitelock, and Catchpole 1989, Hughes & Wood 1990) have been remarked as a distance indicator, such multiplicity is fatal for use as a distance indicator because their characteristics of each strip have not been revealed actually. The MOA (Abe, Allen, Banks et al. 1997; Hearnshaw, Bond, Rattenbury et al. 2000) database of the LMC obtained by large-scale photometry is quite appropriate to study the above problem. Not only related with the multiplicity of the period-

Table 1. The data series of MOA database

	Series 1	Series 2	Series 3
Period	1996 Jan.-1996 Dec.	1997 Jan.-1998 Jul.	1998 Aug.- present
Optics	f/13.5	f/6.25	f/6.25
FOV	$30' \times 30'$	$1^\circ \times 1^\circ$	$0.9^\circ \times 1.38^\circ$
CCD	$1K \times 1K$	$1K \times 1K$	$2K \times 4K$

luminosity relation, the photometric properties must be studied carefully to reveal the nature of AGB variables. Some interesting results of the study of the MOA database is presented.

2. The MOA project

The MOA is the microlensing research project, and the collaboration of about 30 astronomers from Japan and New Zealand. The observational targets are mainly the LMC and Galactic bulge. We observe every photometric night at the Mt. John University Observatory in the center of the South Island of New Zealand using small telescope (61-cm diameter) and large CCD (three chips of $2K \times 2K$ pixels) chips. There are three data series since 1996 (Table 1). The Series 1 is a period of test-drive, while the Series 3 is the current system. In the current Series, the 16 fields around the LMC bar are observed every night and approximately 4.4 million sources are included in the Series 3 LMC catalogue. The curves of transmission of the two color filters and the quantum efficiency of the CCD (SITe, $2K \times 4K$) are shown in Noda, Takeuti, Abe et al. (2002).

3. Red variables

Selection criteria. The selection of regular variables from the MOA database was carried out as the following. In the first criterion (Level 1), 313,706 stars of the MOA database identified with only one DENIS source (Deep Near-Infrared Southern Sky Survey; Epchtein, Deul, Derriere, et al. 1999) were selected. In the Level 2, 'non-photometric' data points were eliminated, and light curves of too small light variation were also removed in the Level 3. In the Level 4 to 8, careful period analysis (PDMM) were performed with necessary eye-estimate to exclude inappropriate samples, and finally, 4,858 red variables were obtained. Amongst the selected stars at the Level 1, K_S magnitudes (the effective wavelength ≈ 2.15 μm) were obtained for 67,107 stars. The histogram of K_S magnitudes is indicated in the left panel of Fig. 1.

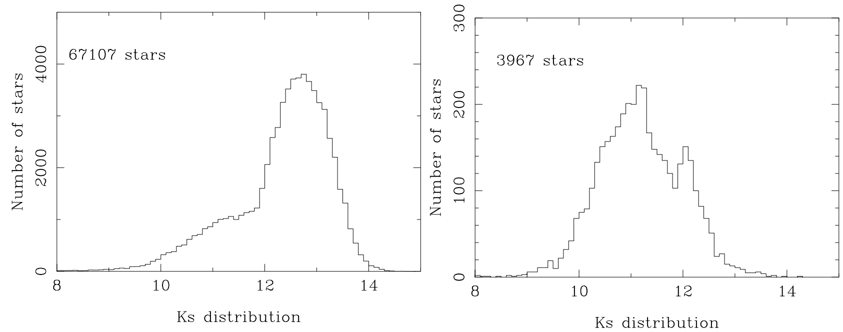

Figure 1. The distribution of the luminosity of non-variable (left panel) and variable (right panel) stars. Two clumps of variable stars are identified.

Two clumps of the red variables. The K_S magnitudes are tabulated for 3,967 stars among the finally selected variable stars. The histogram of K_S magnitudes of these stars is shown in the right panel of Fig. 1. The center of distribution of variable stars was $K_S \approx 11$ mag which corresponded to a bump at the brighter side of the peak in the left panel. The other small peak was found around $K_S \approx 12$ mag in the right panel. Because the large number of non-variables is found fainter than $K_S \approx 12$, it is no doubt about the existence of the fainter clump. The study of intrinsic properties of these two clumps will be important.

4. The period-luminosity diagram

Multiplicity. The K_S magnitudes as a function of $\log P$ for our 3,967 samples is presented in Fig. 2. The dashed line is the $\log P$-K relation for the oxygen-rich Mira sequence by the previous study (Hughes & Wood 1990), while the solid line is the same relation but shifted upwards by 0.29 mag. Some strips were found. In order to investigate the structure, the vertical separation of K_S magnitude from the PL relation by Hughes & Wood (1990) were examined, and six strips (groups $A \sim F$) were defined. The stars labeled with G are ignored because the periods are very short. Stars in the group F were likely long period Cepheids. 3,564 stars were included in the groups $A \sim E$. Note, the group C was the densest strip identified with the classical Mira sequence.

The distribution of amplitude. In Fig. 3, the amplitude histograms of the group $A \sim E$ are presented. The amplitude δR_m was defined as the difference of the magnitudes of the brightest and the faintest bins. In this figure, stars of large amplitude were mainly be-

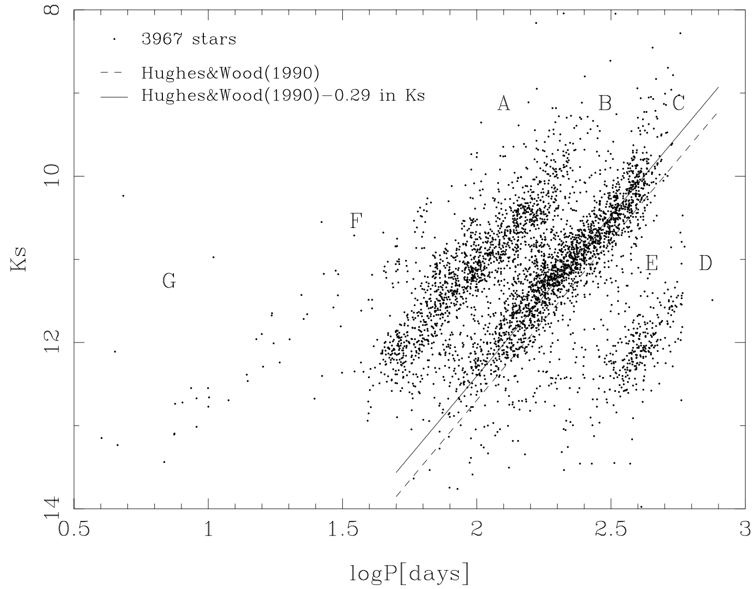

Figure 2. The period-luminosity diagram for 3.967 variables (see text).

longed the group C. For example, 95% of stars whose amplitude were larger than 0.9 were the member of group C.

Regularity of the period. The histograms for the periodicity, θ_r, histogram are presented in Fig. 4. θ_r $(0 < \theta_r < 1)$ is the relative parameter which is defined in the PDMM and indicates regularity of the light variation. Small θ_r indicates high regularity, while large θ_r indicates almost random variation. In this figure, the distribution of θ_r for group C showed it to be almost constant for $0.2 < \theta_r < 0.9$. It is obvious that stars with small θ_r, for example, 88% of stars with $\theta_r < 0.4$ were the member of group C.

The most remarkable sequence. Amongst stars which were satisfied the both condition of $\delta R_m > 1$ and $\theta_r < 0.4$, 96% were the group C component. This means the absolute magnitudes of long-period variables will be estimated properly when the sufficient number of light curves over several cycles are obtained. The luminosity of variables of large amplitude an d high regularity must be estimated by using the period-luminosity relation of group C.

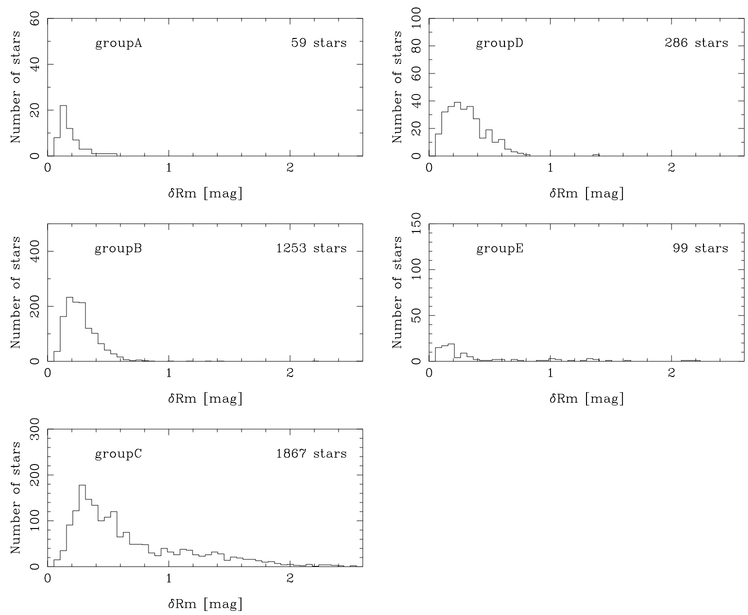

Figure 3. The histogram of amplitude, δR_m, for the five strips.

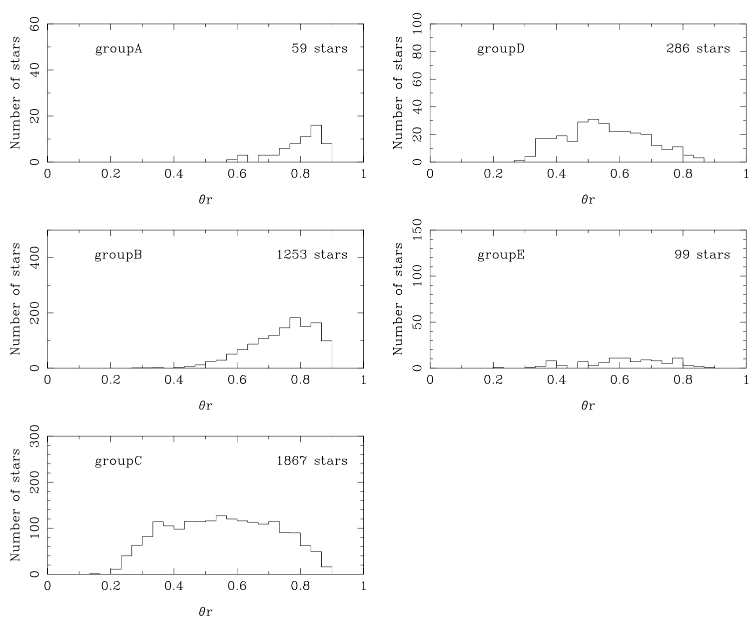

Figure 4. The histogram of periodicities, θ_r, for the five strips.

5. The $(\langle R_m \rangle - K_S, K_S)$ diagram

The color magnitude diagrams, $(\langle R_m \rangle - K_S, K_S)$, for each group are shown in Fig. 5. $\langle R_m \rangle$ indicates the mean magnitude in the MOA red light curve. In this figure, the group name and the number of sample are presented in the each panel. The bottom-right panel indicates the distribution of 67,107 red stars which were identified by DENIS and detected at least in K_S magnitude. Not only variables but also non-variables are plotted in this panel. As reported in the preliminary study by Noda et al. (2002), the variables were located in almost same domain on the CMD.

Because the present samples are very rich in the number, precise comparison of the properties of each group will be interesting. The mean K_S magnitudes of groups A - C correspond to the bright clump beside those of groups D and E are identical with the faint clump. The mean positions of each group on the CMD differ group to group too. Group A is brighter and bluer than group B, and the latter is also brighter and bluer than group C. The examined regression lines showed the slope of the lines for group A, B and C were arranged in the period order (The slope of group A is steeper than group B and so on). In the groups of the faint clump, group D is the fainter and redder one, and the slope of group E is slightly steeper than group D.

6. Other interesting results

RV Tauri-like feature. The light curves of RV Tauri stars are characterized by the alternative deep and shallow light minima. We have found that 13.5 % of the variable star samples show this typical RV Tauri type light curve. It is interesting that the majority of these stars (94 % !) belong to group C. Because the luminosity of these stars are typical to the Mira stars, it is clear that these stars are not the RV Tauri type. It will be mentioned that the RV Tauri-like light curve alone is not the characterized property for the RV Tauri stars.

Eclipsing variables. In the process of selection, we have found many stars showing the light curve typical to the eclipsing binary system. In 348 such stars, 159 stars are located on the same position as group D, and 103 stars are as group C, on the $(\log P,\ K_S)$ diagram. The existence of many eclipsing binaries at the same position as group D on the $(\log P,\ K_S)$ diagram is a new enigma about the AGB stars. It should be noted that group D of our paper is established after excluding the eclipsing binaries. The nature of group D stars will be studied without the connection of the eclipsing binaries.

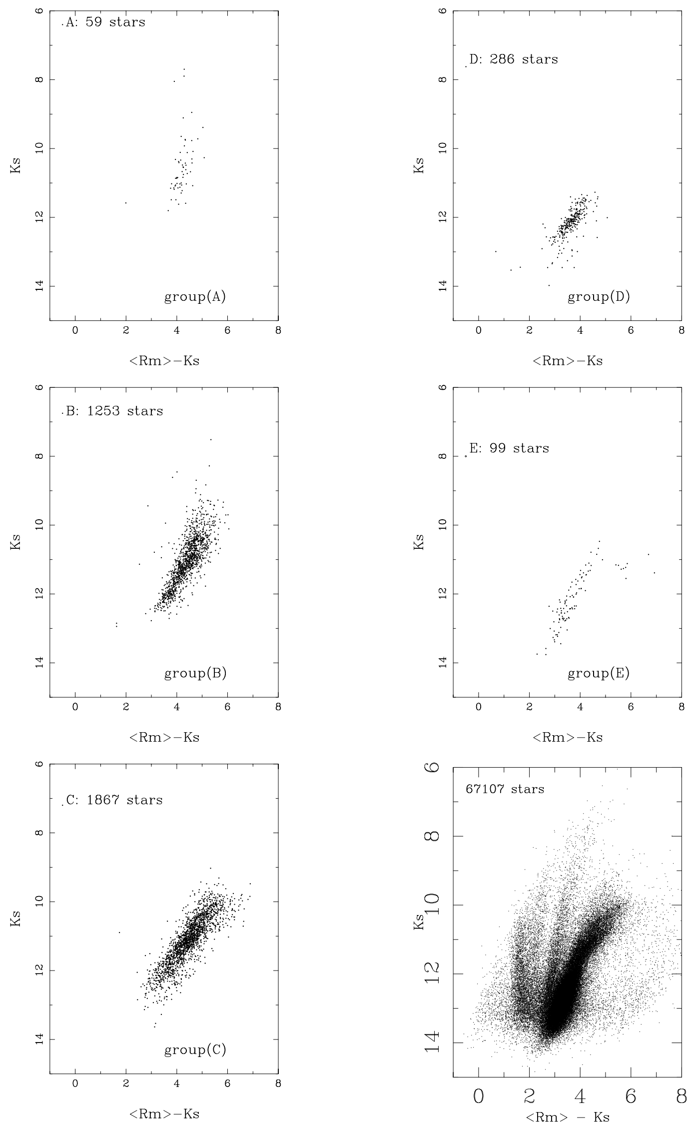

Figure 5. The ($\langle R_m \rangle$ - K_S, K_S) diagram. The bottom-right panel shows the distribution of 67,107 stars which were identified by DENIS and detected at least in K_S magnitude.

Period transition. Difference in the periods was found between the stars tabulated in Hughes & Wood (1990) and the present results. Such a difference was also found between the result of Noda et al. (2002) and the present one. It is found that the period transition of Galactic semi-regulars in the solar neighborhood was also common in the LMC red variables. Together with the RV Tauri-like light curves, these feature will be evidence for multi-mode behavior of the AGB variables.

7. Conclusion

Almost all of large amplitude or highly periodic stars in the LMC were the member of group C which is the most crowded and nearest strip to the classical Mira sequence. For example, the 94% stars of large amplitude ($\delta R_m > 1$) or 88% stars of inferior periodic ($\theta_r < 0.4$) were the group C component. If we require the both conditions, more than 90% were the member of group C strip. It is possible to utilize this type of sequence as a distance indicator, even if multiple relations are found in extra-galactic systems.

In the $(\langle R_m \rangle - K_S,\, K_S)$ diagram, the stars of the five sequences show slightly different features in the order of period. Because all of the variables were found in a limited domain of the CMD, the intrinsic excitation mechanism will be the same, but the difference in the pulsation mode is suggested.

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